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SUSTAINABLE AND BIOENGINEERED CONCRETE FOR ARMOR UNITS OF LOW-CRESTED STRUCTURES

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ABSTRACT

In the last two decades, Eco-engineering has emerged to mitigate and compensate the environmental impacts of man-made structures while integrates benefits to society, being concrete the most widely alternative material used to natural rocks for construction of artificial coastal structures. Over the past three decades, an extensive literature has documented different supplementary cementitious materials (SCMs) to reduce CO_2 emissions from Portland cement, with common SCMs used in marine and coastal structures such as fly ashes, ground granulated blast furnace slags, pozzolanas and limestones. However, there is a need to further investigate the suitability of SCMs for the construction of Low-Crested Structures (LCS) to decrease carbon footprint from concrete production and improve the bioreceptivity of concrete armor units during the breakwater lifetime. A literature review conducted in this study shows several advantages of slag cements compared to other SCMs to reduce carbon emissions and enhance biological colonization and durability of concrete submerged in seawater, identifying surface roughness as the most effective factor in design of bioreceptive concrete. This study also highlights the importance of the type and quantity of cement used in concrete mixes to reduce carbon footprint of the manufacture of concrete armor units of LCS and the implementation of long-term monitoring plans to fully understand the functioning of local communities that develop on concrete surfaces of artificial structures, and thus, to improve the integration of environmental parameters in the field of coastal engineering.

KEYWORDS: Eco-Engineering, Concrete armor units, Low-Crested Structures, Carbon footprint, Bioreceptivity

1 INTRODUCTION

Over the last two decades, Eco-engineering has arisen to alleviate and compensate the impacts of man-made structures, seeking to optimize their ability to sustain biodiversity while integrates benefits to society and harness natural processes, by biocalcification, to increase the strength, durability and adaptability of the structures (Perkol-Finkel *et al.*, 2019, O'Shaughnessy *et al.*, 2020). Concrete is the most used material in the construction industry and comprises a large proportion of coastal structures due to its versatility, high performance and cost-effectiveness. Several studies have recognized its high potential for use in green infrastructure and ecological engineering products even compared to natural rocks. However, the production of the most used hydraulic binder in construction, Portland cement-based concrete, results in about a 7% of the worldwide CO_2 emissions due to the release into atmosphere of about 816 kg of CO_2 per tonne of cement clinker (Barcelo *et al.*, 2013).

In the last three decades, an extensive literature has documented different SCMs as alternative materials to Portland cement to reduce CO_2 emissions from concrete production. The search for new sources of SCMs and innovative materials including recycled materials and industrial wastes is attracting increased interest worldwide (Juenger *et al.*, 2019). Global Warming Potential (GWP) indicators are used to calculate the environmental footprint of different alternative cementitious mixtures, as equivalent kilograms of CO_2 per m^3 of concrete (kg CO_2-e/m^3) and using GWP values of raw materials available in the literature. The use of SCMs for marine and coastal structures has also been investigated, though to a lesser extent in this field, showing common SCMs such as fly ashes, ground granulated blast furnace slags (GGBFS, also referred as slags), pozzolanas and limestones. More recent studies include the partial replacement of coarse aggregate with hemp fibres and recycled shell material (Dennis *et al.*, 2018) or the use of local materials, such as fine marine sediments dredged from ports (Achour *et al.*, 2019) and sea sand as substitutes of fine aggregates of concrete mixes for artificial reefs (Rupasinghe *et al.*, 2024).

The use of concrete as substrate for biological growth requires modification of its primary bioreceptivity, defined by Guillitte (1995) as 'the totality of material properties that contribute to the establishment, anchorage and development of flora and/or fauna'. Efforts in the design of ecologically enhanced coastal structures have mostly focused on the modification of the physical properties of the concrete surface to mimic forms of nature, of which the extensive literature agrees that surface roughness is the most effective factor to enhance the bacterial colonization of cementitious materials (Browne and Chapman 2011, Hayek *et al.*, 2021). Only a few studies have investigated the design of coastal and marine infrastructure by modifying the chemical composition of concrete, of which limited information is published regarding the exact composition of these alternative concretes. In the last three years, there has been a growing interest in the combination of ecological and engineering aspects for its application in the construction of artificial coastal structures, covering concrete durability requirements in marine environment, and providing a more precise definition of the concrete components investigated.

There is a variety of alternative concrete mixtures considering the advances in SCMs on the construction industry, the materials used to construct artificial reefs and the progress on key factors to optimize the colonization of concrete in seawater by marine fauna. However, effort is needed to investigate the suitability of these materials for the construction of breakwaters with a twofold purpose: (1) Decrease CO_2 emissions from the manufacture of concrete armor units of breakwaters; (2) Maximize the bioreceptivity of concrete armor units of breakwaters.

In this work, the most important factors to promote biocolonization of concrete submerged in marine environment are reviewed. Also, different types of cements, SCMs and aggregates are investigated for the proposal of feasible and sustainable concrete mixtures to manufacture armor units of LCS, showing as an example the construction of Cubipod armor units of Homogeneous Low-Crested Structures.

2 MECHANISMS TO ENHANCE THE BIORECEPTIVITY OF CONCRETE ARMOR UNITS

The colonization of any solid surface by micro- and macroorganisms is known as biofouling, which occur at two main stages (Hayek *et al.*, 2020): microfouling (temporal scale from seconds to hours or days) and macrofouling (temporal scale from days to months). Concrete submerged in seawater is rapidly colonized by very small particles, such as bacteria, algae, and other microorganisms (micro-fouling), which secrete substances that form a slimy layer known as biofilm. This bacterial biofilm creates a suitable substrate for the attachment of larger organisms such as oysters, barnacles and other macro-fouling organisms as well as supplies an important food source for grazing invertebrates (Huggett *et al.*, 2009). Concrete has been found to offer a favorable substrate for the establishment of organisms with calcareous skeletons, such as oysters, barnacles and corals, which deposit calcium carbonate onto the concrete surface as result of their physiological activities, being more important as they grow and develop (Risinger, 2012). These organisms have a great ecological value, as ecosystem engineers in many coastal habitats that provide various environmental services, among them, food provision, water filtration or reduction of carbon dioxide dissolved in seawater, through the conversion of carbonates and bicarbonates into calcium carbonate as they build their shells and skeletons (Sella and Perkol-Finkel, 2015, Thomsen *et al.*, 2015).

In the last two decades, Eco-engineering has focused on the increase of the physical bioreceptivity of concrete by introducing physical features comparable in texture to natural rocks. Roughness, complexity and heterogeneity of concrete surfaces, through the inclusion of a varied size of crack pits, holes, grooves and crevices (at the mm-cm scale) (Figure 1), are the main factors considered to provide ecological niches close to natural conditions for a variety of marine species (Hall *et al.*, 2018). Examples of such enhancement mechanisms are the creation of holes (10 cm wide, 3 cm deep) and crevices (0.5-1 cm wide) on Antifer armor units (Sella and Perkol-Finkel, 2015), the modification of complexity at the 4-28 mm scale to create microhabitats on tropical seawalls (Loke *et al.*, 2017) or the multiscale design called BioGeo Ecotile (Kosová *et al.*, 2023) that combines all the physical features (pits, holes, grooves and crevices).

Figure 1. Ecological design of concrete armor units for the construction of breakwaters.

In the last decade, some studies have shown interest in analyzing the influence of the chemical composition of concrete to enhance colonization. While no significant or sufficiently clear differences in biofouling between concrete types were found by some authors, often justified by the ability of both Portland cement and other concrete mixes to allow the growth and development of characteristics and engineering species after one year of exposure in the marine environment (Becker *et al.*, 2020). Other studies recognize the possibility of modifying the chemical composition of the substrate to take advantage of the synergy between physical and chemical properties to favor the biological and ecological behavior of artificial structures, even to reduce the ratio of invasive to local species (Sella and Perkol-Finkel, 2015) or highlight the importance of the cement type on the early colonization effect, which determines the subsequent associated macrofauna communities (Natanzi *et al.*, 2021).

In this sense, a recent study classified the intrinsic parameters that support greater biocolonization from more to less effective in the following order: (1) surface roughness, (2) chemical composition of concrete and type of binder (slag cement instead of Portland cement), and (3) chemical composition of plasticizers added to concrete surface (formwork oil or curing agent) (Hayek *et al.*, 2023). Laboratory experiments showed that treating the surface with a green formwork oil (vegetable oil, such as BIODEM SI 3, spread on the molds before the concrete was poured) or using slag cement instead of Portland cement increased biocolonization at the early stages (during ≈78 days), whereas the application of a curing compound (such as SikaCem®Cure), after stripping of concrete specimens, reduced the bacterial colonization and macrofouling throughout the experiment due to an induced hydrophobic effect on concrete surfaces. The surface roughness was the only parameter that enhanced the biocolonization from the start of macrofouling (after ≈43 days) until the end of the experiment (133 days) (Hayek *et al.*, 2021).

The pH of concrete surface was also found to influence the biological colonization of concrete in seawater due to differences between the pH of concrete surface (pH ≈13) and the pH of seawater (pH ≈8.2). Laboratory tests on concrete specimens showed the influence of this parameter and pre-carbonation of concrete before immersion on the initial bacterial colonization of cementitious materials. When concrete is submerged in seawater, it leaches out alkali metals (potassium, calcium or hydroxide ions) due to the high ionic strength of the concrete pore solution compared to seawater, resulting in a decrease in the pH of the concrete surface and an increase in the pH of seawater depending on the pH values of concrete surface relative to seawater (Hayek *et al.*, 2020). The difference between pre-carbonated samples before immersion (pH =8) and non-carbonated samples (pH =10) was the continuous growth of microorganisms in carbonated samples compared to non-carbonated samples, which showed instability of bacterial biofilm over a period of ≈7-20 days. Additional benefits of pre-carbonation of concrete are the reduction of the inherent concrete alkalinity and change of mineral phases on the concrete surface, with appearance of calcium carbonate, which enhances formation of biofilms (Hayek *et al.*, 2020). A pH of concrete surface between 9 and 10 favors the settlement of larvae (Perkol-Finkel and Sella, 2014), which also indicates the potential effect of this parameter on the macrofauna colonization. Further studies conducted in real projects are essential to explore the effect of these parameters on the macroscopic concrete structure of armor units of breakwaters (Hayek *et al.*, 2021).

From an engineering practice, pre-carbonation may be a difficult mechanism to follow (e.g. carbonated samples achieved after storage of the samples 4 years in laboratory room at 20 °C or after 14 days of immersion in distilled water followed by 7 days in aerated chamber) (Hayek *et al.*, 2020). The use of some pozzolanic additives in concrete may be a feasible method to slightly decrease the pH of concrete surface. For example, the ecological additive used to construct Antifer armor units, mostly based on calcium and silica minerals with 10% of pozzolans, which allows reduction of pH of concrete from 12.5-13.5 (pH of standard concrete) to 9-10.5 (Sella and Perkol-Finkel, 2015, Kenny and Ofer Rozovsky, 2023). The addition of organic materials, such as shell or oyster wastes can also lower the pH of concrete surface and potentially encourage settlement of engineering species such as bivalves (Perkol-Finkel and Sella, 2014), though toxic effects have been found in concretes containing shells, probably due to the decomposition of organic matter attached to the shells (Santos *et al.*, 2023).

To establish clear recommendations for engineering applications, we are still at a very early stage. Studies have mainly based on experimentation in relatively short monitoring periods (most less than one year and a few up to two years) and at reduced scale, providing little information about the exact composition of concrete mixes and much less about their mechanical properties for engineering use. Only one study was found that monitored Antifer concrete units for 6 years of exposure, at 9 m depth, in a breakwater located in the East Mediterranean Sea (Kenny and Ofer Rozovsky, 2023). Holes and crevices of different sizes were created in these units to enhance the physical bioreceptivity of concrete surfaces. Moreover, an ecological additive (referred previously) was added to the slag cement-based mixture (use of CEM III/B) to slightly lower the pH of the concrete units (pH of 9-10.5) and modify its chemical composition to enhance biocolonization (Sella and Perkol-Finkel, 2015). The findings of this study were considered highly relevant to define more robust conclusions, in special for the use of slag cements in engineering applications, both in terms of durability and biocolonization. After 6 years, a slightly increase of the compressive strength was observed, along with an effective bioprotection provided by the carbonate coverage deposited by sessile marine organisms on the concrete surface of the armor units.

Some additional benefits of slag cements are the lower alkalinity (resistance to pH reduction) compared to Porland cements, which promotes biological colonization (Natanzi *et al.*, 2021), as well as the lower metal content (and potentially released by leaching) than Portland cement or fly ash mixtures (McManus *et al.*, 2018). The high surface alkalinity of Portland-based concrete (pH ≈12-13) relative to seawater (pH ≈8) can render an inhospitable or even toxic microenvironment for less alkotolerant marine species (Guilbeau *et al.*, 2003), for periods of 3-6 months or even longer, during which the pH of concrete surface decreases and the pH of seawater reaches stability (Dooley *et al.*, 1999).

Therefore, based on the experience provided by these studies, some recommendations for the design of more eco-friendly concrete armor units of LCS could be stated, as follows: (1) create rough and complex concrete surfaces (at the mm-cm scale), with different holes and crevices of varying size; (2) use of slag cements and, if possible, additives to slightly reduce the pH of concrete surfaces; (3) select environmentally friendly (plant-based or biodegradable) plasticizers, formwork oil or curing agents (if used) and avoid toxic and anti-fouling products.

In general, the coastal environment in which LCS are located can be a suitable full-scale laboratory for long-term monitoring of structures given the relatively easy of access to the structures, typically placed at shallow depths and a short distance from shoreline, and the less disturbed natural conditions at these locations (e.g. compared to seawater surrounding a port infrastructure, where water quality can greatly influence the development and growth of marine fauna on concrete surfaces). In this way, more precise and robust recommendations could be established over time for including ecological aspects and long-term monitoring programs in the design of coastal protection structures.

3 DIFFERENT TYPES OF CONCRETE INGREDIENTS FOR THE CONSTRUCTION OF SUSTAINABLE AND BIO-ENGINEERED LOW-CRESTED STRUCTURES

Concrete is a composite material that mainly contains cement (binder), aggregates and water, with a maximum water to cement ratio and a minimum cement content defined by standards for concrete durability aspects. Thus, cement and aggregates are the main constituents of the concrete mix to select before the construction of LCS to ensure functionality and biological colonization by marine species, in particular the cement type and quantity. The addition of minor constituents (0-5% by cement weight) are also components that may be part of the concrete mixes or the application of work practice products, such as plasticizers to improve the workability of concrete, formwork oil or curing agents.

According to EN 197-1, CEM I (Portland cement, 95-100% clinker), CEM II (Portland cement, 65-94% clinker, with SCMs such as slag, silica fume, pozzolana, fly ash or limestone), CEM III (slag cement with 20-64% clinker), CEM IV (pozzolanic cement with 45-89% clinker) and CEM V (composite cement with 20-64% clinker) are common cements defined by the European standards. From those, CEM II/B-V (21-35% fly ashes), CEM III/A (36-65% slags), CEM III/B (66-80% slags) and CEM V/A (18-30% slags with 18-30% pozzolanas or fly ashes) are some of the cements recommended for the construction of port and maritime infrastructures (RC-16). In terms of carbon footprint, the GWP value estimated for these cements are around 76%, 59% and 33% of that for Portland cement, for CEM II/B-V, CEM III/A and CEM III/B, respectively.

Few studies in the literature allow the comparison of different types of cements in terms of colonization by marine species and engineering performance. Among them, a study of long-term durability and bio-colonization of CEM II/A-LL (80-94% clinker with 6-20% limestones) concretes showed better mechanical strengths than CEM V/A (S-V) (40-64% clinker with 18-30% slags and 18-30% fly ashes) concretes after one year of immersion in marine environment (Georges *et al.*, 2021). A larger biomass was observed in CEM V concretes than CEM II concretes after 360 days of immersion but the compressive strength of CEM V concretes decreased by 28% (Georges *et al.*, 2021).

The most investigated cements in the literature are CEM III (slag cements), of which some advantages have already been presented in section 2. These are: (1) increase durability of concrete due to its microstructure after hydration (Boukhelf *et al.*, 2022), (2) increase early biological colonization of concrete due to its lower alkalinity compared to Portland cement (Natanzi *et al.*, 2021), which provides a better substrate for attachment and growth of marine organisms (Rupasinghe *et al.*, 2024), (3) fulfill inert landfill limits in ecotoxicological analysis, from which CEM III/B 32.5 N-SR is recommended for use in artificial reefs (Santos *et al.*, 2023), (4) contain statistically lower amounts of metal released in controlled leaching experiments compared to concrete containing pulverized fly ash or Portland cement (McManus *et al.*, 2018).

Slag and fly ash are the most widely used SCMs for the manufacture of concrete (Snellings, 2016). Cements containing significant amounts of fly ash and slag are characterized by low heat of hydration, which is very important in the construction of unreinforced concrete structures, with higher strengths after longer curing periods (Król *et al.*, 2020). As an alternative to the limited availability of fly ash and slag, limestone (LL) is increasingly used in cement composition. A synergistic effect was observed in a concrete mixture with 40% clinker replaced by slag and limestone (30% slag and 10% limestone), with better performance than fly ash combined with limestone or slag with fly ash (Król *et al.*, 2020).

The use of local materials as aggregates of concrete mixes are preferred to reduce environmental impacts and favor the colonization of concretes by native marine species. Gravel and sand are common aggregates used in the manufacture of concrete. Recent studies include alternative materials to reduce carbon footprint of concrete production or in case of shortages of these aggregates. For example, the partial replacement of coarse aggregate with hemp fibres and recycled shells, which also enhances the biological colonization of concrete (Dennis *et al.*, 2018). Favorable early colonization was observed in concretes containing limestone and granite aggregates (Natanzi *et al.*, 2021). Limestone and glass sand (0-0.3 mm) used as a substitute for 30% sand also showed good mechanical concrete properties to construct artificial reefs (Boukhelf *et al.*, 2022), with better bio-colonization response observed after two years in glass sand concrete than limestone concrete. Crushed glass sand from broken car windshields, used as recycled fine aggregate to partially replace limestone sand in cement mortars, showed high environmental acceptability as artificial reef material while concrete containing shells showed the highest toxic effect (Santos *et al.*, 2023). Proposals for use of local materials to construct artificial reefs include fine marine sediments dredged from ports, limited to 12.5% of the concrete mix to ensure integrity of mechanical properties (Achour *et al.*, 2019), and sea sand as substitute of fine aggregates of concrete mixes (Rupasinghe *et al.*, 2024).

4 LOW-CARBON CONCRETE FOR ECOLOGICAL CUPIPOD ARMOR UNITS

Cubipod is a massive armor unit with a robust design and high resistance, made of unreinforced concrete, which has been successfully used as armor layers of rubble-mound breakwaters for port infrastructure protection. The most recent research on Cubipod armor units is the construction of Homogeneous Low-Crested Structures (HLCS) for coastal protection (Figure 2a), which is a type of breakwater functionally similar to conventional LCS but with some environmentally advantages. HLCS is composed of Cubipod concrete units distributed homogeneously throughout the structure, without a core and filter layers, which results in a more porous structure (≈50% of porosity) that serves as refuge for marine organisms (Figure 2b), also with the possibility of easy dismantling and reuse (Medina *et al.*, 2020). The high hydraulic stability of HLCS, shown in 2D experimental tests, and the expected minimal maintenance of these structures contribute to the development of mature assemblages on the concrete surfaces of the structures (Airoldi *et al.*, 2005).

Yet, these units have smooth and low heterogeneity concrete surfaces. Therefore, there is still a higher potential for ecological enhancements through the creation of some design that increases overall surface roughness and complexity (e.g. introducing holes in the cubic faces where the protrusions are supported and crevices in all concrete surfaces).

(a) (b)

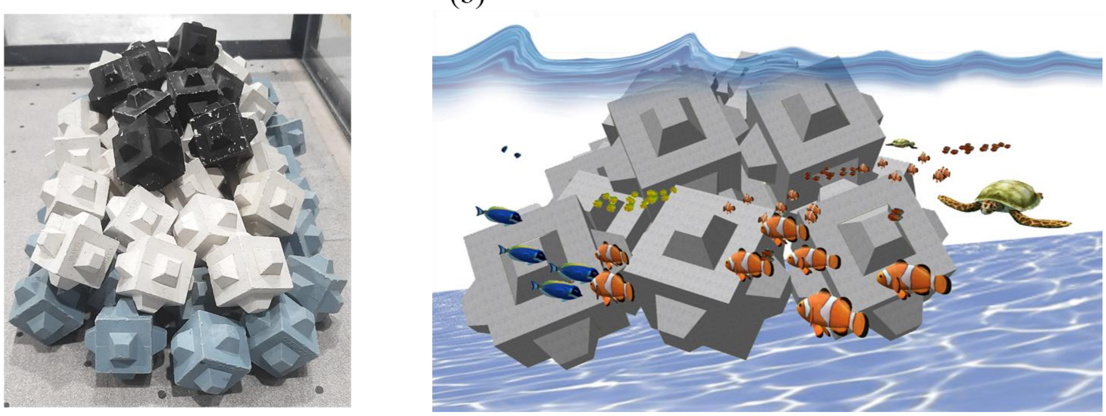

Figure 2. (a) Model of a 3-layer Cubipod HLCS; (b) Sketch of a 2-layer Cubipod HLCS in marine environment.

Cubipods are usually manufactured near the breakwater installation site, transported by trucks and handled by a crane on a barge for placement and construction of the breakwater. Few maintenance operations are expected during the lifetime of these structures and easy dismantling, so it is thought the major CO_2 emissions from the installation of HLCS will occur due to concrete production. Although a compressive strength of 20 MPa is recommended for cubes and Cubipod armor units under 60-tonnes and up to 30 MPa for 140-tonnes units to achieve the concrete tensile strengths required for durability aspects (Medina and Gómez-Martín, 2016), the typical concrete used to manufacture these armor units in Spain shows a compressive strength fck ≈58 MPa (Medina *et al.*, 2011). This concrete mixture is composed of 350 kg/m^3 of cement CEM I 42.5 R, which is even a higher quantity of cement than necessary to meet the standards (300 kg/m^3). Consequently, the typical concrete manufacture of these structures may generate avoidable carbon emissions.

Six concrete mixes (M1 to M6 in Tables 1 to 3) tested in marine environment for breakwater construction were selected from the literature to compare the influence of the type and quantity of cement in the total carbon footprint of concrete production. CEM I, CEM II/B-V, CEM III/A and CEM III/B are the cement types compared in these mixes. The concrete mixes were grouped by similar 28-day compressive strengths (fck), from lowest to highest strength in this order: concrete mix M1 (fck: 31 MPa) described in Table 1, suitable for the construction of Cubipod armor units and other massive concrete units of similar durability performance, such as cubes; concrete mixes M2 to M4 (fck≈ 56-59 MPa) described in Table 2, and concrete mixes M5 and M6 (fck≈ 62-73 MPa) described in Table 3 with higher compressive and tensile strength recommended for the construction of non-massive armor units, such as the bulky armor units Accropodes or Ecopodes (https://www.concretelayer.com/). The ingredients of concrete mixtures M2 to M6 could also be used to manufacture Cubipods, though with a lower amount of cement to achieve the recommended strengths and avoid unnecessary carbon emissions. Granite, quarzitic sand, gravel and natural magnetite for high-density concrete are the aggregates used in the concrete mixes. Concrete mixes M1, M5 and M6 also contain superplasticizer (Table 1 and Table 3), though no information is available concerning the possible anti-fouling effects of these products.

Table 1. Concrete mix M1 (fck: 31 MPa) (Burcharth *et al.*, 2015).

Constituents	kg/m^3
CEM II/B-V 32.5 R	340
Granite and quarzitic sand, max size 70 mm	1898
Water	160
Superplasticizer	2

Table 2. Concrete mixes M2, M3, M4 (fck ≈ 56-59 MPa) (Becker *et al.*, 2021).

M2 (fck: 59.1 Mpa)		M3 (fck: 58.4 MPa)		M4 (fck: 56.4 MPa)	
Constituents	kg/m^3	Constituents	kg/m^3	Constituents	kg/m^3
CEM I 42.5 R	320	CEM III/A 42.5 N	320	CEM III/B 42.5 N-LH/SR	320
Magnadens 20 s	2122	Magnadens 20 s	2112	Magnadens 20 s	2107
2-8 mm Gravel	95	2-8 mm Gravel	95	2-8 mm Gravel	95
0-2 mm Sand	667	0-2 mm Sand	664	0-2 mm Sand	662
Water	160	Water	160	Water	160

Table 3. Concrete mixes M5, M6 (fck ≈ 62-73 MPa) (Hayek *et al.*, 2021).

M5 (fck: 72.25 MPa)		M6* (fck: 62.92 MPa)	
Constituents	kg/m^3	Constituents	kg/m^3
CEM I 52.5 R	350	CEM I 52.5 R	140
		CEM III/A 42.5 N	210
Gravel 4/6	249	Gravel 4/6	249
Gravel 2/4	418	Gravel 2/4	418
Sand 0/4	806.67	Sand 0/4	806.67
Water	158	Water	158
Superplasticizer	3.5	Superplasticizer	3.5

*M6 is composed of a combination of CEM I and CEM III/A, 40% and 60% by weight, respectively.

Carbon emissions, given by the GWP indicator and expressed in kilograms of CO_2 equivalent per cubic meter of concrete (kg CO_2-e/m^3), as shown in Figure 3, were calculated using the GWP values of concrete constituents (kg CO_2-e per tonne of constituent in Table 4) and the quantity of ingredients considered in each mixture (Tables 1 to 3).

Table 4. Carbon footprint of concrete constituents.

Constituents	GWP (kg CO_2-e/t)	References
CEM I	860	1
CEM II/B-V	660	2
CEM III/A	510	3
CEM III/B 42.5 N-LH/SR	289.97	https://www.holcim.es
Fly Ash	150	1
Slag	170	1
Coarse aggregate- Granite	45.9	Flower and Sanjayan, 2007
Coarse aggregate- Basalt	35.7	Flower and Sanjayan, 2007
Fine aggregate (sand)	13.9	Flower and Sanjayan, 2007
Tap water	0.91	Botto, 2009
Superplasticizer	2980	Schiefer and Plank, 2023

[1] Average CO_2 emission based on GWP literature data (Haist *et al.*, 2022); [2] GWP value based on 75% clinker and 28% fly ash; [3] GWP value based on 49.5% clinker and 50.5% slag.

A considerable variation in GWP values of concrete mixes as a function of the amount and type of cement is observed in Figure 3. For example, the difference in M5 and M2, where 30 kg less of cement CEM I produces a reduction of around 26 kg CO2-e per m^3 of concrete (in grey in Figure 3b and 3c). Figure 3 also shows the influence of cement type on carbon emissions, with the highest GWP values given by concrete mixes composed of cements CEM I and CEM II (M5, M2 and M1). Considering similar compressive strengths and the same quantities of cement and other concrete constituents, the reduction in carbon emissions using CEM III/A (M3) or CEM III/B (M4) is shown in Figure 3b, with around 31% and 50% reduction of CO2-e per m^3 of concrete for M3 (CEM III/A) and M4 (CEM III/B), respectively, compared to M2 (CEM I). Likewise, the comparison between M5 and M6 also shows the considerable reduction of emissions (≈21%) by replacing 60% of CEM I with CEM III/A in concrete mix M6 (Figure 3c). The use of low-emission cements can be seen as an important factor to consider in the manufacture of concrete armor units to reduce global carbon emissions from breakwater construction. Where possible, local materials should also be considered to reduce the environmental impact of transporting raw materials to the concrete manufacturing site.

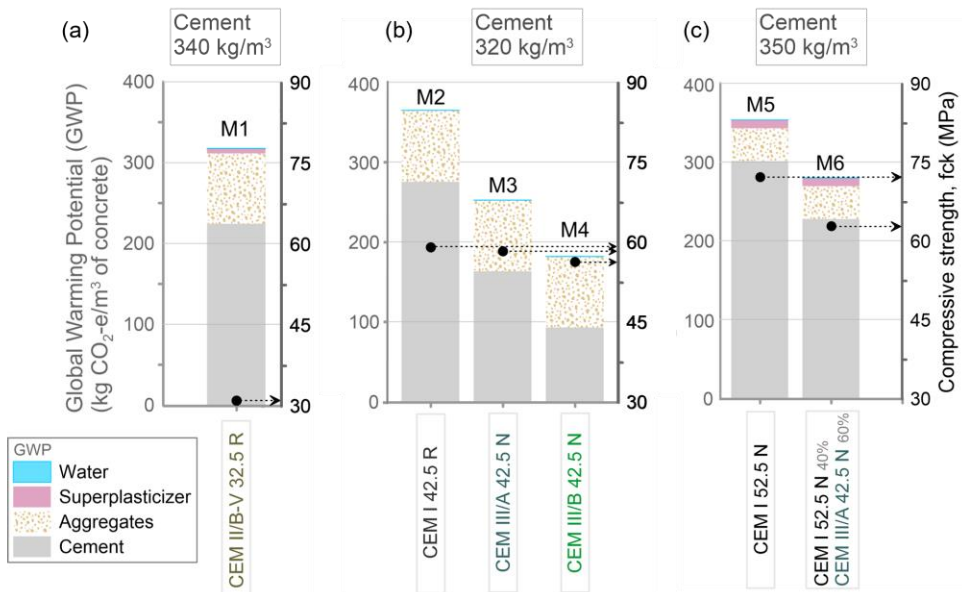

Figure 3. Carbon emissions (GWP) on the left and 28-days compressive strength, fck, on the right corresponding to concrete mixes with different type and quantity of cement: (a) fck: 31 MPa, 340 kg cement/m^3 ; (b) fck≈ 56-59 MPa, 320 kg cement/m^3; (c) fck≈ 62-73 MPa, 350 kg cement/m^3.

Promoters, contractors and designers usually focus attention on construction costs, and thus, it was also important to analyze the influence of cement type on the unit construction cost of HLCS. An approximation was made using the expression to calculate the construction costs of Cubipod armors of mound breakwaters, Cc (€/m^3) in Equation (1), which includes costs of concrete supply, manufacture, handling, placement, facilities and equipment (Medina and Gómez-Martín, 2016).

$$C_c\left[\frac{€}{m^3}\right] = (265 + \mathrm{CON}) + 1.00\left[10^5\left(\frac{1}{ln(V_c W_c)}\right)^2 - 10^4\left(\frac{1}{ln(V_c W_c)}\right)\right] \quad (1)$$

where CON (€/m^3) is the unit cost of the concrete supplied, V_c is the total volume of concrete used in the armor to manufacture Cubipod units and W_c is the weight of Cubipod units.

The unit cost of concrete supplied (CON) was calculated for the six concrete mixtures, M1 to M6 (Table 5), using cement prices provided by Holcim Spain S.A.U (in December 2023) and an estimated cost of 10 € per tonne of aggregates if local aggregates are used, or transported over short distances (up to ≈30-40 km) (personal communication with site manager of Pavasal company). For comparison of unit construction costs of HLCS (Cc), a 3-layer Cubipod HLCS of 100 m length was considered, at 4 m depth, composed by 672 Cubipods with a nominal diameter (Dn) of 1.2 m and 4 t weight (Wc), resulting in a total volume of concrete Vc ≈1162 m^3 (Mashadyan, 2022).

Table 5. Cost of concrete supplied, CON, and breakwater construction costs, Cc, for different types of cements in concrete mixes.

Concrete mixes	fck (MPa)	Cement	Cement price (€/t)	CON (€/m^3)	Cc (€/m^3)
M1	31	CEM II/B-V 32.5 R	140 [1]	66.6	549.8
M2	59.1	CEM I 42.5 R	150 [2]	76.8	560.0
M3	58.4	CEM III/A 42.5 N	155	78.3	561.5
M4	56.2	CEM III/B 42.5 N	168.5	82.6	565.8
M5	72.2	CEM I/52.5 N	150	67.2	550.4
M6	62.9	CEM I/52.5 N CEM III/A 42.5 N	150 155	68.3	551.5

[1] Prices of CEM II/B-M (S-L) 42.5 R and [2] CEM I 52.5 R were available and used as an approximation.

Figure 4c shows a 1% increase in construction costs by using CEM III/B (M4) instead of CEM I (M2); figure 4d shows a 0.2% increase in total breakwater construction costs by using concrete mix M6 instead of M5. The type of cement used in concrete mix M1 (CEM II/B-V 32.5 R) is the cheapest (see Table 5) but the worst from the point of view of carbon emissions and compressive strengths (see Figure 3). It is convenient to highlight the importance of considering potential additional construction costs when choosing a low-emission binder, which should be a key aspect in reducing the overall environmental impact of concrete production.

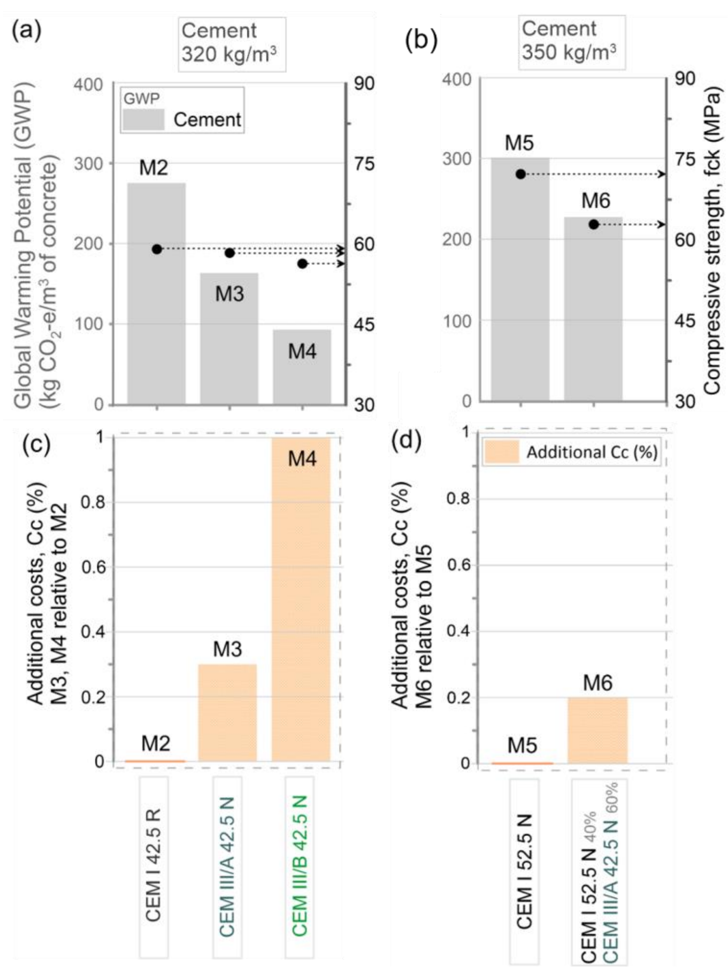

Figure 4. Comparison of carbon emissions (GWP) and additional construction costs of breakwaters (Cc) for concrete mixes of similar compressive strengths and different cement types: (a) and (c) fck ≈ 56-59 MPa; (b) and (d) fck ≈ 62-73 MPa.

5 SUMMARY AND CONCLUSIONS

Surface roughness, chemical composition of concrete, type of binder, and chemical composition of plasticizers added to concrete surface (formwork oil or curing agent) are the most important factors to enhance the biocolonization of submerged concrete elements in seawater. The analysis of carbon emissions of six concrete mixes composed of CEM I, CEM II/B-V, CEM III/A and CEM III/B showed the importance of the type and quantity of cement used in concrete manufacture to reduce the total carbon footprint of concrete production. Based on the experience provided by the studies in the literature and the analysis of carbon emissions carried out in this paper, some recommendations for the design of more eco-friendly concrete armor units of LCS could be stated as follows:

(1) Create rough and complex concrete surfaces (at the mm-cm scale), with different holes and crevices of varying size to provide ecological niches close to natural conditions for a variety of species.

(2) Use of low-binder cements to reduce carbon emissions and consider potential additional construction costs of this type of cements, in particular slag cements (CEM III/B) showed several advantages compared to other SCMs and Portland cement in terms of concrete durability, enhanced biological colonization and content of metals potentially released by leaching. The quantity of cement used for concrete mixes should be limited to meet standards and mechanical properties for engineering performance and concrete durability in marine environment.

(3) If possible, use additives to slightly reduce the pH of concrete surfaces and favor early biological colonization of concrete (pH≈ 9.0 to 10.5).

(4) Select environmentally friendly (plant-based or biodegradable) plasticizers, formwork oil or curing agents (if used) and avoid toxic and anti-fouling products.

(5) Where possible, local materials should also be considered as aggregates of concrete mixes to reduce the environmental impact of transporting raw materials to the concrete manufacturing site and favor the colonization of concretes by native marine species.

(6) Consider new alternatives of SCMs to the limited availability of fly ash and slag, such as limestone combined with slag due to synergistic mechanical properties observed (e.g. 40% of clinker replaced by 30% slag and 10% limestone) and the use of alternative materials to common aggregates, such as limestone and glass sand (0-0.3 mm) as a substitute for 30% sand or local fine marine sediments (limited to 12.5% of the concrete mix) and sea sand as substitutes of fine aggregates of concrete mixes.

The example of construction of Cubipod armor units of Homogeneous Low-Crested Structures allows to highlight some environmental advantages of this type of LCS: (1) the high hydraulic stability and expected minimal maintenance of the structures contribute to the development of mature assemblies on the concrete surfaces; (2) the higher porosity of the structure (≈50% porosity) favors the biocolonization of the structure and its use as refuge by marine fauna; (3) the easy dismantling and reuse contribute to reducing the overall carbon footprint of manufacturing concrete armor units.

Specific research and on-site observations are essential to fully understand how physical and chemical properties of concrete affect the colonization of species in a particular marine environment. It is also important to carry out long-term monitoring plans, with a better understanding of the functioning of local communities that develop on concrete surfaces of artificial structures and their evolution over time. Sharing progress with the scientific community and users is also considered of great relevance, with the definition of the exact composition of concrete mixtures investigated. Thus, it will eventually help to improve the integration of environmental parameters in the field of coastal engineering.

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